Forest assisted migration under uncertainty

Minh Ha-Duong, Ankur Shah

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October 29, 2013

Abstract

We consider the question of whether assisted migration of a valuable timber species is appropriate when faced with deep climate uncertainties. In France, Current official recommendations for sessile oak (*Quercus petraea*) are based on performance under historical climate conditions and do not take global climate change into account. Can foresters reduce the cost of forest regeneration by assisted migration? This note illustrates a decision-making method to select tree seed provenance in the face of deep uncertainty about future climate, in which the relative probabilities of future climates are unknown. Our initial results are purely illustrative, as we employ a simplified cost model of forest regeneration and placeholder data for provenances and climate futures. We look forward to improve it in collaboration with AMTools partners.

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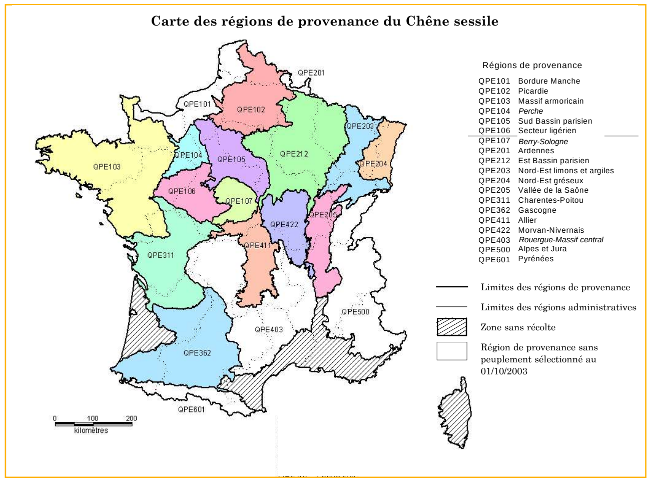


Figure 1: *Quercus petraea* provenance origins

1 Introduction

Quercus petraea, commonly called sessile oak (chêne sessile or chêne rouvre in France), is one of the most important trees in Europe, both for its historical and cultural significance as well as its contemporary sylvicultural value. The market for *Quercus petraea* seeds in France recognizes 19 provenance regions, as shown in the map in Figure 1 and table in Figure 2. Official recommendations from the French Ministry of Agriculture[1] provide recommendations of which seeds to use for each region in France.

Current official recommendations for sessile oak (*Quercus petraea*) in the Picardy region of France suggest plantation of the local provenance (QPE 102: *Picardie*) for optimal yield, and two other provenances (QPE 101: *Bordure Manche* and QPE 212: *Est bassin parisien*) for acceptable results. These recommendations are based on historical climate conditions and do not take global climate change into account.

In this manuscript, we describe a method to compare the cost of forest regeneration for each of N available provenances under a variety of possible climate futures. Rather than assigning probabilities to possible climates, we incorporate multiple worldviews as to the relative likilihoods of future scenarios. The method prefers one option to another if and only if the former is expected to outperform the latter in every worldview considered. As the cost of establishment of a forest considers tree performance only in the regeneration phase ($0-10$ years), running the model for one location at multiple target planting dates will produce recommendations which evolve with that location's climate.

[1] `http://agriculture.gouv.fr/IMG/pdf/chene_sessile-2.pdf`

Code RP	Nom de la région de provenance	Surface (en milliers de km^2)	Altitude moyenne (min-maxi) (m)	Localisation, roches dominantes	Données climatiques			Espèces principales présentes dans la région de provenance (% en volume)	Observations
					Précipitations moyennes annuelles (saison de végétation)	Température moyenne annuelle (saison de végétation)	Déficit hydrique relatif annuel(pour T>7°C)		
QPE 101	Bordure Manche	20	100 (5-315)	Bordure Manche : en général crayeux	830 mm (360 mm)	9,9°C (13,8°C)	11,6 % 13,2 %	*Fagus sylvatica : 34%* *Quercus robur : 14%* ***Quercus petraea : 11%*** *Fraxinus sp. : 7%* *Betula sp. : 6%* *Pinus sylvestris : 5%*	1 peuplement sélectionné pour 16,5 ha au 10/10/03
QPE 102	Picardie	28	100 (5-285)	En général crayeux	710 mm (340 mm)	9,9°C (14,3°C)	15,0 % 17,0 %	*Quercus robur : 18%* *Fagus sylvatica : 14%* ***Quercus petraea : 13%*** *Fraxinus sp. : 12%* *Carpinus betula : 8%*	3 peuplements sélectionnés pour 195 ha au 10/10/03
QPE 103	Massif armoricain	62	100 (5-415)	Massif armoricain : roches cristallines, grès, schistes	850 mm (330 mm)	11°C (14,7°C)	15,9 % 17,3 %	*Quercus robur : 22%* ***Quercus petraea : 16%*** *Pinus pinaster : 13%* *Castanea sativa : 10%* *Fagus sylvatica : 8%* *Pinus sylvestris : 6%*	2 peuplements sélectionnés pour 38,08 ha au 10/10/03
QPE 104	Perche	8,1	160 (25-325)	En général crayeux	730 mm (320 mm)	10,3°C (14,6°C)	17,8 % 20,0 %	***Quercus petraea : 39%*** *Quercus robur : 21%* *Fagus sylvatica : 8%* *Betula sp. : 5%*	5 peuplements sélectionnés pour 1261 ha au 10/10/03
QPE 105	Sud Bassin parisien	20	130 (5-345)	Calcaire, marnes, sables	650 mm (315 mm)	10,4°C (15,0°C)	19,2 % 21,8 %	***Quercus petraea : 38%*** *Quercus robur : 16%* *Pinus sylvestris : 10%* *Carpinus betula : 7%* *Castanea sativa : 6%*	8 peuplements sélectionnés pour 782,62 ha au 10/10/03
QPE 106	Secteur ligérien	16	100 (15-255)	En général crayeux Vallée de la Loire: alluvions	680 mm (305 mm)	11,0°C (15,4°C)	20,8 % 22,6 %	***Quercus petraea : 33%*** *Pinus pinaster : 18%* *Quercus robur : 18%* *Castanea sativa : 9%* *Pinus sylvestris : 6%*	7 peuplements sélectionnés pour 2692,24 ha au 10/10/03
QPE 107	Berry-Sologne	10	155 (75-425)	Sologne : sables Nord du Berry : souvent calcaire	730 mm (340 mm)	10,6°C (15,2°C)	16,1 % 18,2 %	*Quercus robur : 27%* ***Quercus petraea : 19%*** *Pinus sylvestris : 18%* *Pinus nigra spp. Laricio : 7%* *Betula sp. : 6%*	8 peuplements sélectionnés pour 965 ha au 10/10/03
QPE 201	Ardennes	1,8	245 (95-495)	Schistes et grès recouverts de limons acides	980 mm (450 mm)	9,3°C (14,0°C)	5,9 % 6,6 %	*Picea abies : 26%* ***Quercus petraea : 24%*** *Quercus robur : 17%* *Betula sp. : 11%* *Carpinus betula : 5%* *Fagus sylvatica : 5%*	1 peuplement sélectionné pour 16 ha au 10/10/03
QPE 212	Est Bassin parisien	47	215 (25-635)	Champagne : souvent crayeux Plateaux calcaires	820 mm (390 mm)	9,8°C (14,6°C)	11,5 % 12,9 %	***Quercus petraea : 19%*** *Quercus robur : 18%* *Fagus sylvatica : 15%* *Carpinus betula : 12%* *Fraxinus sp. : 5%*	10 peuplements sélectionnés pour 353 ha au 10/01/02
QPE 203	Nord-Est limons et argiles	19	305 (145-835)	Substrat à dominante argilo-marneuse, notamment avec le plateau lorrain Grès, calcaires Limons dans le Sundgau	910 mm (450 mm)	9,3°C (14,5°C)	7,3 % 8,0 %	***Quercus petraea : 24%*** *Fagus sylvatica : 23%* *Quercus robur : 15%* *Carpinus betula : 10%* *Fraxinus sp. : 6%* *Picea abies : 6%*	24 peuplements sélectionnés pour 446 ha au 10/10/03
QPE 204	Nord-Est gréseux	11	390 (105-1410)	Vosges : gréseux ou cristallin Vallée du Rhin : alluvions	1 040 mm (510 mm)	9,1°C (14,5°C)	7,5 % 8,0 %	*Abies alba : 29%* *Picea abies : 21%* *Fagus sylvatica : 18%* *Pinus sylvestris : 10%* ***Quercus petraea : 8%***	15 peuplements sélectionnés (dont 2 non autochtones) pour 628,29 ha au 10/10/03
QPE 205	Vallée de la Saône	17	265 (125-915)	Lit majeur : alluvions - Reste : argiles, limons...	910 mm (460 mm)	10,5°C (15,8°C)	8,7 % 9,6 %	***Quercus petraea : 27%*** *Quercus robur : 17%* *Castanea sativa : 10%* *Carpinus betula : 9%* *Fagus sylvatica : 6%*	4 peuplements sélectionnés pour 50 ha au 10/10/03
QPE 311	Charentes-Poitou	35	90 (5-345)	Dominante de calcaires	800 mm (350 mm)	11,7°C (16°C)	17,3 % 18,5 %	*Pinus pinaster : 24%* *Quercus robur : 23%* *Castanea sativa : 14%* ***Quercus petraea : 10%*** *Quercus pubescens : 9%*	5 peuplements sélectionnés pour 471, 18 ha au 10/10/03
QPE 362	Gascogne	47	190 (5-1110)	Dominante de calcaires, marnes	890 mm (410 mm)	12,4°C (16,8°C)	14,2 % 15,1 %	*Quercus robur : 28%* *Quercus pubescens :18%* *Castanea sativa : 11%* ***Quercus petraea : 9%*** *Pinus pinaster : 8%*	8 peuplements sélectionnés pour 174,76 ha au 10/10/03
QPE 411	Allier	19	520 (85-1600) (*)	Sud du Berry : plutôt calcaire Basse Combraille : plateau cristallin Monts d'Auvergne volcaniques	910 mm (465 mm)	9,7°C (14,3°C)	8,0 % 9,0 %	***Quercus petraea : 28%*** *Quercus robur : 16%* *Fagus sylvatica : 14%* *Pinus sylvestris : 10%* *Picea abies : 7%* *Abies alba : 6%*	12 peuplements sélectionnés pour 1289,63 ha au 10/10/03
QPE 422	Morvan-Nivernais	17	350 (135-995)	Morvan : granites, gneiss, schistes Nivernais : terrains d'origines variées (sables, argiles, calcaires, marnes...)	910 mm (450 mm)	10,0°C (14,9°C)	8,2 % 9,2 %	***Quercus petraea : 29%*** *Pseudotsuga menziesii:14%* *Quercus robur : 14%* *Fagus sylvatica : 7%* *Abies alba : 7%* *Carpinus betula : 7%*	7 peuplements sélectionnés pour 456 ha au 10/10/03
QPE 403	Rouergue-Massif Central	60	610 (35-1600) (*)	Roches cristallines et métamorphiques Roches volcaniques dans les monts du Velay	1 060 mm (485 mm)	9,6°C (14,2°C)	7,8 % 8,7 %	*Pinus sylvestris : 17%* *Quercus robur : 13%* *Castanea sativa : 11%* *Fagus sylvatica : 11%* *Abies alba : 10%* *Picea abies : 8%* *Pseudotsuga menziesii :6%* ***Quercus petraea : 5%***	4 peuplements sélectionnés pour 2,43 ha au 10/10/03
QPE 500	Alpes et Jura	45	840 (65-1600) (*)	- Jura : calcaire - Préalpes calcaires - Alpes internes : cristallin, métamorphique	1 190 mm (560mm)	8,9°C (14°C)	5,7 % 6,6 %	*Picea abies : 25%* *Abies alba : 20%* *Fagus sylvatica : 14%* *Pinus sylvestris : 10%* *Larix decidua : 5%* ***Quercus petraea : 4%***	Pas de peuplement sélectionné au 10/10/03
QPE 601	Pyrénées	11	1020 (125-1600) (*)	- Haute chaîne cristalline et métamorphique - Bordure : plutôt calcaire	1 210 mm (560 mm)	9,8°C (13,8°C)	3,7 % 4,9 %	*Fagus sylvatica : 43%* *Abies alba : 24%* *Pinus uncinata : 5%* ***Quercus petraea : 3%***	Pas de peuplement sélectionné au 10/10/03

(*) : Le chêne sessile n'est plus présent au dessus de 1 600 m d'altitude (Rameau et al., 1989), les régions de provenance sont limi-

Figure 2: *Quercus petraea* provenance characteristics

2 Determining Option Performance

The decision-making method uses growth data for the N provenance options considered $(a_0, a_1, a_2, \ldots a_N)$ to determine an order of preference for plantation. Performance is evaluated across multiple potential climates, and multiple worldviews of how likely each potential climate is, at any given point in time.

We evaluate the economic performance of a provenance by computing the expected cost to have a well-established stand of that provenance. We consider a stand to be well-established when the mean height of the trees reaches $h = 300cm$. At this stage in the stand's regeneration, a canopy effect takes hold and significantly reduces the risk of competition to the young trees, as well as associated maintenance costs to the forester [REF]. We also correlate this height to the end of the period of high sensitivity to water and nutrients that marks the establishment phase [REF].

If we assume that provenances:

- share the same initial costs (planting, seedling acquisition)
- would be planted at the same density
- incur the same yearly costs (maintenance, weeding, opportunity cost of land)

then we can substitute calculating the number of years until establishment for the cost of establishment, as all other costs are considered equal.

The number of years until establishment is just the total required growth divided by the seedings' yearly growth rate. We assume the growth rate is uniform across the stand and constant over time. Naturally, a stand's growth rate depends largely on its provenance, leading to a different time to establishment for each provenance. However, when we consider the performance of a stand under a climate different from its historical norm, we must adjust its known provenance growth rate by our expectation of its performance – for better or worse – in the new climate.

Through analysis of provenance tests that compare the growth of populations from a variety of different provenances in a variety of different test sites [REF], we can sketch a relationship between a provenance's growth rate and its climate distance from its home climate.

Expressed mathematically:

$$t_{a_i,w_j} = \frac{h - h_0(a_i)}{Growth(a_i) * ClimateAdjustment(a_i, w_j)} \tag{1}$$

That is, the time to establishment (t_{a_i,w_j}) is different for each option (a_i) and climate (w_j) pair, and is the quotient of the desired growth differential and the adjusted growth rate of the provenance.

For each option a_i, we need the following information:

- : $h_0(a_i)$: initial seedling height (cm)

- : $Growth(a_i)$: seedling growth rate (cm/year) at climate of origin
- : $Origin(a_i)$: variables describing climate of origin (MAT, etc)
- : $ClimateAdjustment(a_i, w_j)$: function or table of how growth rate is scaled by climate. Adjustment at origin climate will be 1.

The values t_{a_i,w_j} are then calculated for each option and climate pair and used as the performance function in the decision model.

For the demonstration run of the model, we use placeholder parameters for the population options (Table 1), climate futures (Table 2), and climate adjustment (Table 3).

Using this placeholder data, we generate a performance matrix populated by t_{a_i,w_j}, the years to establishment, shown in Table 4

As we can quickly see, t varies widely, across both climates and options.

3 Making Decisions Among Options

Though we now have calculated the performance of each option in each climate, we still are in no position to choose among options or make recommendations. This is because we don't know the relative liklihood of each climate future. The intuitive approaches in such a case, if a bit naive, are as follows:

- pick one distribution of probabilities of probable futures (often assuming they all have equal liklihood) and calculate expected performance using the chosen probabilities.
- look at the performance of all options in all scenarios, and choose the option whose worst-case performance is the best.

The first approach runs significant risk of the optimizing a decision for a future that will most likely not exist, and which may not share signficant charactersitics with the future that does come to pass. The second approach is heavily risk-averse and is limited by the worst case scenario, often leading to inaction, unsatisfactory performance, or the lack of a solution.

We demonstrate a third approach, incorporating maximization behavior from the former and robustness behavior from the latter technique, by using multiple perspectives, or worldviews, regarding the distribution of future climates.

Expressed mathematically, our L worldviews are:

$$V_1, V_2, \dots V_L$$

$$V_l = \{p(w_1), p(w_2), \dots p(w_K) | \sum p_{w_k} = 1\}$$

where $p(w_i)$ notes the percentage liklihood given to climate future w_i according to perspective V_l. For the demonstration run of the model, we use the

Table 1: Placeholder Population Parameters

```
each column represents one provenance
(a in our model)
row 1: initial seedling height (cm)
row 2: seedling growth rate (cm/year)
row 3: home climate (MAT in C)

19.3 20.6 18.4 21.4 19.6
32 31 30 29 28
-1 0 1 2 2.5
```

Table 2: Placeholder Climate Parameters

```
each column represents one potential climate
(s in our model)
row 1: MAT in C

0 1 2.5 3 3.5 4
```

Table 3: Placeholder Climate Adjustments

```
value in row i, column j
represents scaling in growth rate
for provenance i in climate scenario j
value will be 1 for "home climate"

.95 .85 .70 .58 .73 .70
1 .95 .85 .7 .65 .6
.90 1 .80 .65 .6 .55
.70 .9 1.12 .9 .8 .7
.6 .75 1 1.1 .95 .85
```

Table 4: Option Performance Matrix: value at row i, column j represents years to establishment of option a_i under climate w_j

```
9.200000 10.300000 12.500000 15.100000 12.000000 12.500000
9.000000 9.500000 10.600000 12.900000 13.900000 15.000000
10.400000 9.400000 11.700000 14.400000 15.600000 17.100000
13.700000 10.700000 8.600000 10.700000 12.000000 13.700000
16.700000 13.400000 10.000000 9.100000 10.500000 11.800000
```

parameters for the worldviews listed in Table 5. In a future iteration of the model, we can collect perspectives from experts and key stakeholders, and even run the model "live" in front of them, taking their worldviews into account.

Table 5: Placeholder Worldviews: each row indicates one worldview; the first column indicates the year of the prediction, and each column j represents the probability assigned to climate $j - 1$

```
// for deep uncertainty version of the model
// each line represents distribution of probability
// among the possible climate states
// 1st column is the year
2015 .27 .23 .15 .15 .15 .05
2015 .18 .18 .08 .18 .23 .09
2015 .15 .15 .15 .25 .15 .15
```

Applying our worldviews to the performance values in Table 4 gives us the expected performance (E_{V_l}) of each option in the eyes of each worldview:

$$E_{V_l}(t(a_n, \tilde{w})) = \sum_{l=k}^{K} p(w_k) * t(a_n, w_k) \tag{2}$$

in which we express the future climate as ($\tilde{w}$) to remind us that climate is an uncertain variable. Using the placeholder worldviews above we calculate the expectations shown in Table 6.

At this point, using our calculated expectations, we define an option as preferred ($\succ$) to another if and only if it has a better expected performance according to *every* Worldview considered:

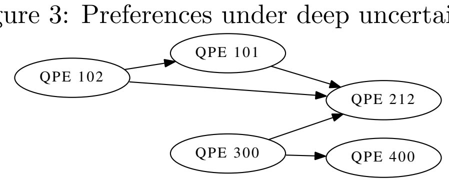
$$a_i \succ a_j \iff \forall_l E_{V_l}(u(a_i, \tilde{s})) - E_{V_l}(u(a_j, \tilde{s})) > 0 \tag{3}$$

The preferences expressed, shown in Figure 3, are rational for a risk-neutral decision-maker seeking best expected performance across multiple climate futures.

Table 6: Expectations: value at row i, column j represents expected years to establishment of option a_i under worldview V_j

11.42	11.11	12.25
10.98	11.05	11.93
12.08	12.22	13.23
11.54	11.00	11.48
12.62	11.33	11.63

Figure 3: Preferences under deep uncertainty



4 Discussion

We conclude our presentation by summarzing the results, comparing them with other treatments of uncertainty, and pointing in the direction of our future research endeavors.

4.1 Summary

The graph shown in Figure 3 provides a tool for decision-makers who need to choose from a group of diverse options under conditions of deep uncertainty. Each arrow represents improved performance of one option over another, in *every* worldview considered. Even a simple iteration of the model serves to clarify some points about the decision-making process:

- The existence of a preferred option is not guaranteed.
- The choice of which Worldviews to include determines the solvability of the model. The decision-process around the model must take this into account and plan for iterations to relax or constrain Worldviews as necessary.
- Preferred options will likley *not* be optimal according to any single world-view or state of the world, but will be robust to all predictions considered

In a typical decision scenario, we will look for the existence of any relationship $a_n \succ a_0$, and stay with a_0 in the absence of such a preferred option.

4.2 Comparisons

How do the preferences shown in Figure 3, derived from taking multiple world-views into account, differ from the two intuitive treatments of deep uncertainty described in section3?

4.2.1 Precise probabilities, or Subjective Expected Utility

Running the model as if we knew the probabilities of future climate worlds collapses our decision-making process from deep uncertainty to quantifiable risk. As it is equivalent to choosing one worldview to use for all calculations, the decision to use one perspective is often controversial. Decision-makers faced with total uncertainty may sometimes assume all futures are equally likely (the Laplace assumption). Besides the obvious concerns of presenting quantified recommendations based on imaginary probabilities, calculating performance in this way ties the results heavily to the (often controversial) choice of inclusion of plausible worlds.

When run with precise probabilities from one world-view (let us choose the first line of Table 5), the model gives the expectations shown in Table 7 and the preferences displayed in Figure 4. When run with the Laplace assumption, that all potential worlds are equiprobable, the model gives the expectations shown in Table 8 and the preferences displayed in Figure 8.

4.2.2 Scenario Analysis

To compare the deep uncertainty results with the divergence of solutions for different climatic scenarios, we run the model with as many Worldviews as climate futures ($K = L = 6$). This procedure has the advantage of showing us the range of performances for each option, but gives us very little information on how to proceed. The expectations are equivalent to the performance matrix in Table 4, and the Figure 6 shows clearly, no preference can be establish. That is to say, there is no option whose worst case is better than another option's best case.

4.3 Future research directions

In this paper, we have aim to show the potential usefulness of our decision model for making decisions under uncertainty in the forest context. The relevance of the performance analysis rests on the assumption that the establishment phase of a young forest is sufficently challenging and expensive that we can make decisions based on population performance during this phase, rather than overall productivity at harvest.

We would now like to run the model with data from provenance tests, to apply our model to the initial problem mentioned in section 1. Future iterations would add climate data as to the frequency of heat and cold waves at each of the sites considered and the vulnerability of each population to heat and cold waves, both of which are potentially fatal at a large scale for tree populations.

While we would like to offer decision support on the larger question of productivity over the life-time of the plantation, we leave the question for future work and longer-term datasets.

Table 7: Expectations under one worldview: value at row i, represents expected years to establishment of option a_i

```
11.57
11.32
12.52
11.71
12.54
```

Figure 4: Preferences under one worldview

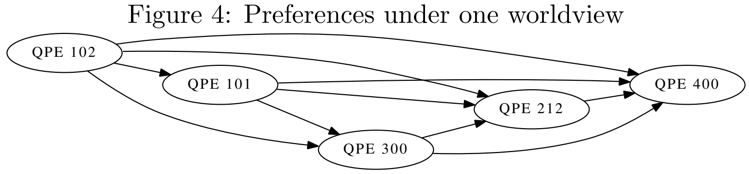


Table 8: Expectations for equiprobable case: value at row i, represents expected years to establishment of option a_i

```
11.93
11.82
13.10
11.57
11.92
```

Figure 5: Preferences under equiprobable case

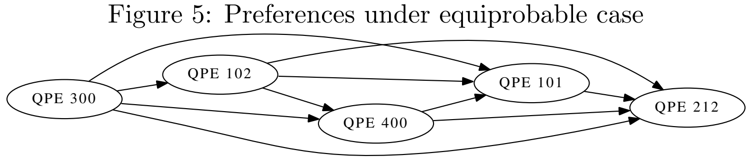
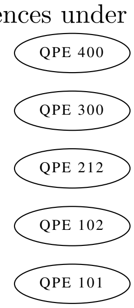


Figure 6: Preferences under Scenario Analysis



For more in-depth cost analysis, we could also use density of trees (trees/ha) and plantation cost (/$treeor$/ha), and their variation with provenance.

All of our analysis so far suffers from the assumption of risk-neutrality: that looking at the mean of a population gives us sufficient information for decision making. Having data regarding the variance of the parameters considered (primarily growth rates) would allow us to perform a much-more nuanced analysis.

Finally, it seems logical that thorough attempts to take climate change into account would consider the possibility of mixed stands (portfolios) of provenances, and we would like to extend our work in that direction as well.